

Now You See It, Now You Don't—The Pattern of Production of Certain Resonances

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(Dated: August 5, 2004)

Abstract

We try to motivate from QCD a pattern of production in various reactions of (non)exotic resonances. A higher penalty for extra $q\bar{q}$ production in e^+e^- collisions than in collisions with a nucleon target may explain the absence of exotic multi-quark states in e^+e^- . We also briefly address the doubly charmed baryons and the utilization of QCD inequalities in connection with possible new hadronic states.

PACS numbers:

INTRODUCTION

The issue of selective production of various hadronic states under different circumstances has renewed and enhanced urgency. It is particularly the case for the 1540 MeV pentaquark. By now the K^+n or K^0p resonance has been seen in many γ proton and neutrino proton (or deuteron/nuclei) experiments[1]. It has however not been seen in several e^+e^- and $p - \bar{p}$ collider experiments to be reported in the upcoming ICHEP. A related example is that of the new $D_s(2362)$ seen by the Selex hyperon beam charm experiment in both $D_s\eta$ and D^0K^+ decay modes but not found in e^+e^-S colliders. Selex found also evidence for doubly charmed baryons which were not confirmed by other experiments.

In many cases in the past some scientists discovered something new, which others, using the same or different methodology, failed to verify. Every conflict was eventually settled and a consensus reached. In most cases the conservatives prevailed and the apparent new discovery was discarded. In a handful of cases *all* experiments were correct and a novel idea resolved the apparent conflicts. A prime, recent example is that of the Solar neutrinos. The Vacuum *and* MSW effects combine to account for the perplexing pattern of solar neutrinos observed in different experiments with different sensitivity for neutrinos of different energies and flavors.[2]

We wish to point out that for the exotic pentaquark and a “crypto-exotic” $D_s(2632)$ the second possibility may not be ruled out.

THE ARGUMENT FOR DIFFERENT PRODUCTION RATES OF EXOTIC AND NON-EXOTIC HADRONS IN e^+e^- COLLISIONS

The BaBar and Belle e^+e^- colliders at $W = m(\Upsilon 4S) \sim 10.5$ GeV, were designed to study the physics of heavy (b) flavor decays and CP violation. Yet these experiments may be the best tool for studying hadrons made of uds and c quarks and mesons in particular.

Jointly BaBar and Belle will collect several billion $e^+e^- \rightarrow c\bar{c}, s\bar{s}, d\bar{d}$ and $u\bar{u}$ collisions. With 4π geometry, excellent momentum and angular resolution and good particle identifi-

cation these experiment have reconstructed all known (mesonic) resonances and a few more, and so far this has mainly been a by-product of studying B decays!

The following pattern is theoretically expected for e^+e^- colliders: Ordinary non-exotic resonances made of a quark and an anti-quark are more copious than exotic resonances made of two quarks and two anti-quarks. This can help determine the quark content of the state under study.

Our claim may seem surprising. On average \sim ten pions are produced in e^+e^- collisions 10.5 GeV. Viewing each pion as a $q\bar{q}$ pair we have ten light quarks, and ten antiquarks produced in each collision. In this case there is no preference of $q\bar{q}$ non-exotics with two quarks and antiquarks relative to $q\bar{q}q\bar{q}$ exotics with altogether four quarks and anti-quarks.

This simplistic argument is wrong and the preferred production of non-exotics in electron positron collisions is model independent, tracing back to the $1/N_c$ expansion in QCD.

Thus let us follow the evolution of the system. After the $e^+e^- \rightarrow$ virtual $\gamma \rightarrow c\bar{c}$ or $q\bar{q}$ with $q = u, d, s$ collision, the primary high energy quark and anti-quark emerge as highly virtual “hot lines”. Subsequent evolution “splits” off additional gluons and quark-anti-quark pairs with decreasing virtuality and energy which is shared by an increasing number of constituents. Eventually confinement sets in and rather than use the picture of quark and gluons we revert to hadrons: $q\bar{q}$ non-exotic mesons, qqq baryons (and antibaryons), glueballs and potentially also $q\bar{q}q\bar{q}$ exotics.

At what stage does this happen and what is the average mass M of these primordial hadronic clusters? Several arguments suggest that $M \sim 1.2\text{-}2$ GeV [3]. The perturbative evolution proceeds until a sufficient number of extra, light quark pairs have been produced so that the invariant masses of $q_i\bar{q}_j$ which are neighboring in rapidity is $\sim M$. These clusters are *color singlets* made of quarks and anti-quarks or glueballs. The mass of the lightest glueballs $\sim 1.5\text{-}2$ GeV confirms the above estimate of M . The glueballs and the highly excited mesons are broad and quickly decay into lighter $q\bar{q}$ mesons and pions in particular.

The key observation suggesting suppressed production of $q_i\bar{q}_j q\bar{q}$ exotics relative to the corresponding non-exotic $q_i\bar{q}_j$ is the following: The production of each $q\bar{q}$ pair during the first stage of the M cluster production is suppressed. This suppression stems from the

$\alpha_{(QCD)} \sim 1/N_c$ factor and is even stronger in nonperturbative models e.g[4] where the pairs are produced via Schwinger's mechanism. The $q\bar{q}q\bar{q}$ exotics are heavier than ~ 1 GeV and should therefore be produced in this first stage when color singlet clusters of such masses are generated. Hence the production of exotics is suppressed relative to that of non-exotics by $1/N_c$ and most likely by much more. Similar reasoning apply to decays of heavy quarks, i.e. B decays, despite the fact that the primary decay of the b quark to c and two light quarks yields three energetic quarks and we have also the spectator light quark from the initial B.

As the final state pions are mainly "secondary" emerging from the decaying resonances/clusters, the relevant number of primary pairs initially produced is much smaller than the above naive estimate of ten pions and ten quark–anti-quark pairs per collision.

We proceed next to discuss several cases where this pattern of suppressed production of exotics in electron positron colliders may manifest, and where it may help identify the state in question.

i) The production of the new $X(3870)$ Belle state [5] confirms this general pattern *if* it is exotic, say $c\bar{c}(u\bar{u} + d\bar{d})/2^{(1/2)}$. The original Belle experiment[5] shows on the same $(J/\psi)\pi$ pi invariant mass plot the (radially excited) non-exotic $^3S_1 c\bar{c} \psi'$ state, and of $X(3870)$. Both states are expected to have branching fractions into $(J/\psi)\pi\pi$ of the same order of magnitude[6]. The large $\sim 300(!)$ ratio of the non-exotic and exotic peaks manifests then mainly the larger cross for producing the former. The interpretation of an exotic $X(3870)$ as a near threshold $D^*\bar{D}$ state [8] and the Deuson model suggested for many other exotics[9] also imply strongly suppressed production.[7],[10]

ii) The BaBar $D_s(2317)$ state is strongly produced in B decay [11]. Thus our general considerations suggest that it is indeed the missing non-exotic $c\bar{s}$ [12], rather than a $c\bar{s}q\bar{q}$ [13].

iii) The $0^+ a(980)$ and $f(980)$ states could be four quark states—as suggested by R.Jaffe[20] or P-wave $0^{(++)} s\bar{s}$ non-exotics. In the first case these states should be less prominent in BaBar and Belle than ω, ρ or $q\bar{q}$ P wave non-exotic resonances.

iv) The new $D_s(2632)$ Selex state [14] was not been seen to date in electron positron colliders. If it were exotic: $c\bar{s}(u\bar{u} + d\bar{d})/2^{(1/2)}$ then the suppressed production of exotics in

e^+e^- colliders provides (some) excuse for that. Other aspects of the Selex data argue more strongly against a non exotic $c\bar{s}$ assignment. The observed ratio $r = \Gamma(D^0 K^+)/\Gamma(D_s^+ \eta)$ is 0.16 ± 0.06 . However phase-space prefers the first higher Q value ,mode by \sim factor of two, $s\bar{s}$ production which must occur in the decay into $D_s + \eta$,is suppressed relative to the production of $u\bar{u}$ (or $d\bar{d}$) in the decay into DK by ~ 3 and finally the η is only $\sim 50\%$ $s\bar{s}$ in its flavor content. Jointly these three factors yield a predicted r (for a non -exotic $D_{sJ}^+(2632)$) ~ 12 , seventy times larger than the observed value.

The remaining puzzle of why this state with a large Q value is so narrow is shared by the pentaquark, the prime exotic candidate to which we turn next.

PRODUCTION OF EXOTICS AND NON-EXOTICS OFF NUCLEONS

The non-production of complex hadronic structures, eg the He^5 nucleus and its anti-particle, in e^+e^- colliders is not an argument against their existence. One should look for He^5 in the natural neutron + He formation channel. A similar though weaker case is next made against using the lack of evidence for pentaquark in e^+e^- colliders as a reason to doubt its existence.

(The lack of evidence for $J^P = 1/2^+ \Theta$ and any of its expected entourage of $1/2^-$, $3/2^+$ or other states in the natural K^+ -neutron (namely K^+ -deuteron scattering) formation channel, is however problematic [16]).

It is well known and readily explained [4] that the production of baryons in e^+e^- colliders is suppressed by a factor of 20 or more relative to that of mesons. This is much more the case for pentaquark production requiring five(!) pairs be produced.

Within a specific model we found a dramatic realization of these general expectations.[16] (anti)Theta production in e^+e^- collisions was suppressed in this model by a large $10^5 - 10^6$ factor which may explain why the pentaquark has not seen to date in BaBar and in Belle.

In γ -nucleon collisions, since at least three (and if we allow the gamma to $s\bar{s}$ conversion even four) of the quarks required in order to make up the pentaquark are there initially, Θ

photoproduction should have far larger cross sections. The same is true in $N\bar{N}$ annihilations where we have altogether six initial quarks and antiquarks. In particular -in such annihilations at rest or low energies we would expect to have often a diquark from the proton and an anti- diquark from the anti-nucleon to often form cryptoexotic $qq\bar{q}\bar{q}$ tetraquarks. If the latter were reasonably narrow than the tetraquarks should have been discovered in the famous CERN LEAR experiment. If however the lightest (and narrowest!) tetraquarks are significantly lighter than $W(\text{annihilation}) \approx 2 \text{ GeV}$ several pions accompany on average the tetraquark in each annihilation event generate a severe combinatorial background impeding such a discovery[17],[18].

The above comments notwithstanding, many features of the pentaquark and its production pattern remain puzzling.

The above strong suppression obtained by using the chromoelectric flux tube model (CFT) for particle production in electron positron collisions[4] *and* a CFT model with two junctions and one anti-junction for the pentaquark.[18],[17] This CFT model for the pentaquark was motivated by the small width $\Gamma \sim \text{O}(\text{MeV})$ suggesting that the pentaquark is very different from the decay channel hadrons. The model naturally corresponds to the diquark-diquark-anti-strange-quark picture for the pentaquark ([19] and also [15]). This picture along with some extensions[16] of QCD inequalities [21] imply new undiscovered vector meson tetraquarks lighter than a GeV. Furthermore in the CNN CFT model the pentaquark in γ nucleon collisions should be associated with such tetraquarks and *not* with the observed Kaons.

Also independently of any specific model we have argued [18] that the pentaquark production in the various photoproduction reactions of the pentaquark are inconsistent with the natural kaon exchange models: the large $\Theta - KN$ couplings required clash with bounds on the width of the pentaquark [15],[22],[23],[24].

In general, meson baryon is the ideal formation channels of pentaquarks as the initial state contains the required four quarks and antiquark. In KN collisions no non-exotic s channel states exist and even in $\bar{K}N$ or πN collisions the total crosssection is dominated for most energies by exotic namely pentaquark intermediate states. Conventionally these state were assumed to be very broad. Further the exotic spectrum was expected to be denser than

the non-exotic reflecting the larger number of degrees of freedom. The many overlapping resonances would then blend into the smooth energy variation observed. If the pentaquark survives this view may be challenged: many resonances may have been too narrow and missed in past rough scans [17]. Also if some pentaquarks are indeed three body diquark diquark anti-quark systems their spectrum need not be (much) denser than that of baryons.

One final comment on the use of nuclear targets. It is well known that the charge radius of Nucleons is larger than that of mesons and multi-quark exotics are likely to be even more extended. Thus heavy nuclear targets may filter out—particularly at higher collision energies, the exotics and more readily pass smaller more compact mesons. Under special circumstances this may be evaded. In the CFT model some tetra-penta etc quarks are topologically stable and will not break while traversing the nucleus. Also for low collision energies the many initial quarks can even enhance production of multi-quark structures.

SOME COMMENTS ON THE SELEX DOUBLY-CHARMED BARYONS AND ON QCD INEQUALITIES

The doubly-charmed baryons provide yet another example of conflicting experimental evidence for new states. Can theory provide some additional hints? Earlier higher theoretical estimates for the mass of the doubly charmed baryons cannot exclude the Selex discovery. Indeed prior to the discovery of the $D_s(2317)$ BaBar 0^{++} state most theoretical estimates of its mass were ~ 50 - 100 MeV higher (and its expected broad $K - D$ width discouraged searching for it...)

However the large EM mass splitting in the Doubly-Charmed Baryon (DCB) doublet:

$$\delta(m)|DCB = m_{(ccu)} - m_{(ccd)} \sim 12\text{MeV}$$

is problematic. It is inconsistent with the splitting in the Charmed Meson (CM) doublet:

$$\delta(m)|CM = m_{(c\bar{d})} - m_{(c\bar{u})} = 4.8 \pm 0.1\text{MeV}$$

Detailed QCD/potentials modeling and quarkonium phenomenology [26] imply an average $c - \bar{c}$ separation in J/ψ of .4 Fermi. The cc -diquark system inside the DCB is bound by *half* the color forces operative in the J/ψ , and hence the cc system is larger than J/ψ .

An extreme assumption helping compare the EM mass splittings in the DCB and in the CM is that the cc diquark is a pointlike “Heavy” system of twice the mass and charge of the charmed quark. This grossly distorts the cc EM self energy—which, however, cancels in the ccu-ccd difference). Concentrating the heavy quark charges at one point and using the same, universal, wave function of the light anti-quark or quark for heavy color source mass m_c or $2m_c$, both enhance the EM splitting. Since we look for an *upper* bound on this splitting we adopt both approximations. The electromagnetic part of the isodoublet splitting in the DCB is therefore at most twice that in the CM. Using $m(d) - m(u) \sim 3\text{--}5$ MeV we predict that $\delta(m) \text{---DCB} < 3.6 - 0$ MeV conflicting with Selex data.

Before concluding we recall some simple, semi-empirical rules that evolved from from QCD inequalities due to Weingarten,[27] Vafa and Witten [28] and Witten[29] and Nussinov [30] This subject was extensively reviewed in a recent report [21].

Let us mention here a few pertinent examples. The pseudoscalar mass inequalities

$$m_{ps}(q_i \bar{q}_j) > 1/2[m_{ps}(q_i \bar{q}_i) + m_{ps}(q_j \bar{q}_j)]$$

follow directly from the QCD lagrangian if we neglect “Flavor disconnected” diagrams with intermediate pure glue states. This is indeed justified for $q = Q = c$ or b . Hence the lightest $B_c 0^-$ state with reported mass of $6.4 \pm .4$ GeV, [31] *must* be heavier than the average of the η_c and η_b masses. Hopefully the η_b will be discovered soon and this QCD prediction verified. More heuristic analoge inequalities are expected for the 3^S vector mesons made of heavy quarks. suggesting a symilar inequality involving $\Upsilon^4 S, J/\psi$ and the lightest vector B_c state. Doubly-charmed baryons should satisfy the meson baryon inequalities: $m(ccq_i) > 1/2[m(J/\psi) + a.m(D_i^*) + (2-a).m(D_i)]$ with $a=2$ for $S=3/2$ and $a=1/2$ for $S=1/2$ DCB’s. ($S=\text{spin}$) [21] In the baryon sector various convexity relations between baryon masses have been motivated. For multiple charmed baryons these imply: $m(cud) = m(\Lambda_c) > 1/2[mccq + m(\text{Nucleon})]$ and $m(ccu)(3/2^+) > (1/2)m(ccc)(3/2)^+ + m(cud)(3/2)^+$ Jointly thses relations bracket the mass of the lightest $S = 1/2$ DCB in the range of 3 GeV-3.63 GeV.

SUMMARY

Despite recent progress in Lattice QCD we still lack reliable ab initio calculations of hadron masses particularly with one or more light (u, d, s) quarks. In looking for guidance as to where new discoveries are likely and/or for “theoretical confirmation” of putative findings experimenters often turn to the many hadronic models developed prior to and alongside QCD. These include potential models for massive constituent quarks, chiral lagrangians and chiral perturbations, and QCD sum rules. Some intriguing offshoots of the chiral approach and large N_c limit are the Skyrme/chiral soliton models. In certain extensions of the original SU(2) flavor model to SU(3) a very light [32] and narrow [33] $1/2^+$ pentaquark state emerges as part of an SU(3) antidecuplet. The last work, which has been subsequently challenged [34] and [35], motivated Nakano et al. to embark on their discovery work. A different example is provided by the D_s states. After discovery it was realized that such states were suggested in a special spontaneous chiral symmetry breaking pattern where some parity doublet regularities survive [36]

In the present and in many earlier works we note that more basic/elementary considerations of unitarity, heavy quark universality, QCD inequalities and general semi-empirical patterns may be critical in assessing discoveries of new hadronic states. Also a conflicting patterns of production of exotic and non-exotic resonances in various reactions need not imply that some of the experiments are wrong and may instead be due to rather simple underlying physics.

ACKNOWLEDGEMENTS

I would like to thank M. Purohit for bringing to my attention the new D_s Selex state, and to him and to C. Rosenfeld and J. Wilson for careful reading and useful comments on the manuscript.

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